The Higgs Factory: A Theorist's Perspective

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Higgs Factory panel discussion

OUTLINE

1. Anticipating the Higgs discovery
2. The decoupling limit
3. Toward a precision Higgs program

Outline

1. Theoretical implications of a Higgs boson discovery
   - discovering the Standard Model–like Higgs boson
   - ruling out the Standard Model Higgs boson

2. The decoupling limit of the Higgs sector

   - The Higgs sector as a window to new BSM physics
   - The two Higgs doublet model (2HDM)
   - The Higgs sector of the MSSM
   - Decoupling attributed to tree-level effects
   - Decoupling attributed to radiative loop effects

3. Toward a precision Higgs program at a future Higgs factory
   - Is the SM-like Higgs boson *the* SM Higgs boson?
   - Interpreting deviations from SM Higgs behavior

1. Higgs boson couplings in the Standard Model

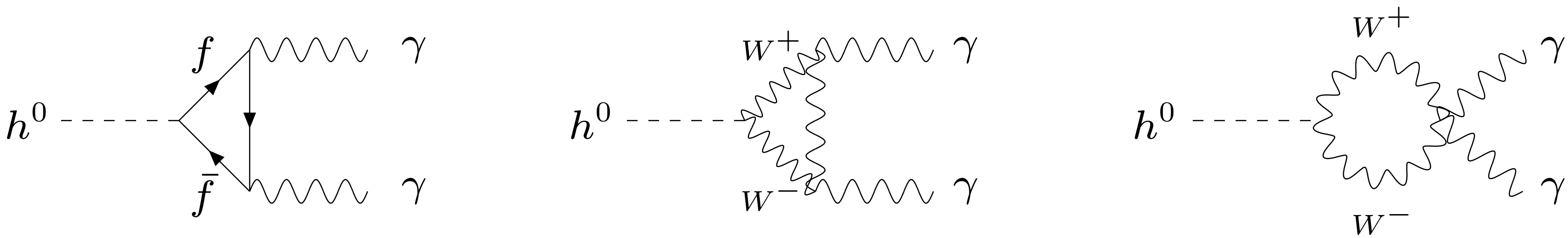
At tree level (where $V = W^\pm$ or Z),

Vertex	Coupling
hVV	$2m_V^2/v$
$hhVV$	$2m_V^2/v^2$
hhh	$3m_h^2/v$
$hhhh$	$3m_h^2/v^2$
$hf\bar{f}$	m_f/v

At one-loop, the Higgs boson can couple to gluons and photons. Only particles in the loop with mass $\gtrsim \mathcal{O}(m_h)$ contribute appreciably.

One-loop Vertex	identity of particles in the loop
hgg	quarks
$h\gamma\gamma$	$W^\pm$, quarks and charged leptons
$hZ\gamma$	$W^\pm$, quarks and charged leptons

Example: Higgs boson coupling to photons. At one-loop, the Higgs boson couples to photons via a loop of charged particles:



In the Standard Model (SM), the properties of the Higgs boson are completely fixed once the Higgs mass is determined. To claim a discovery of the SM Higgs boson, it is necessary to measure the SM Higgs couplings and verify that they coincide with the predicted SM values.

Such measurements can only be performed with limited precision at the LHC. Thus, the LHC can never claim a discovery of the SM Higgs boson; at best the LHC can claim the *discovery of a SM-like Higgs boson*.

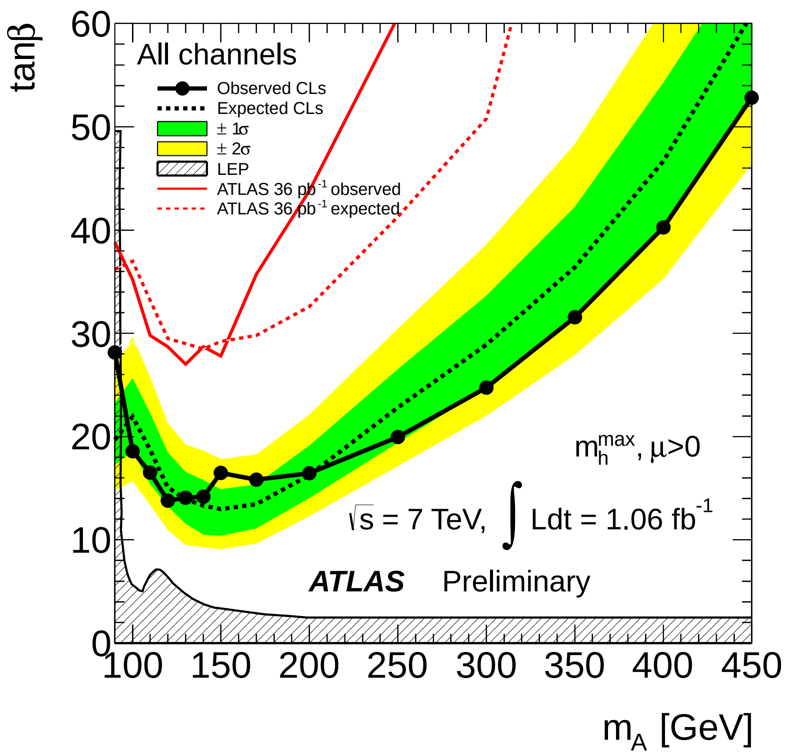
In contrast, if (some of) the measured values of the Higgs couplings differ significantly from the predicted SM values, then it is possible to *rule out the SM Higgs boson* at the LHC.

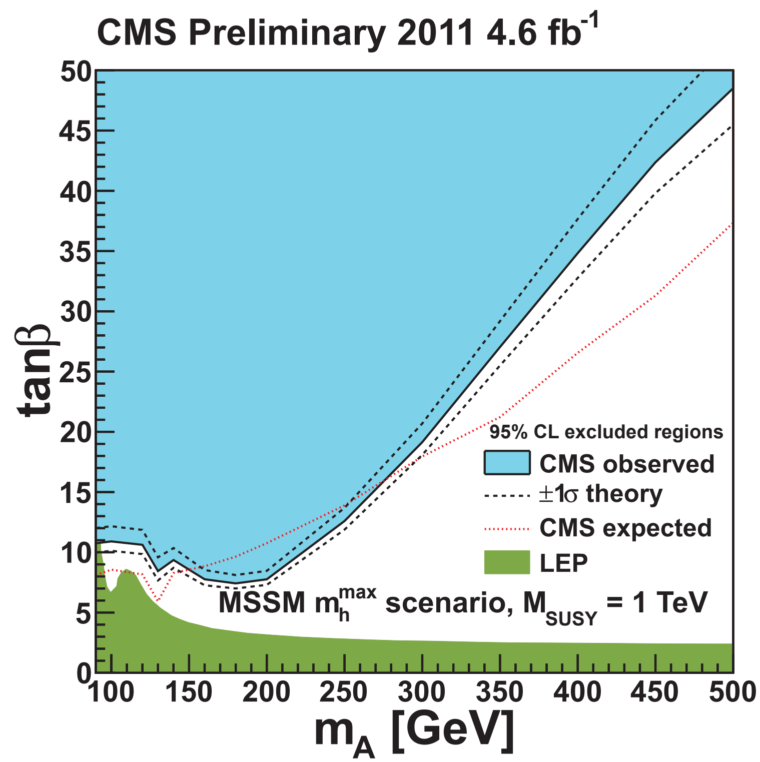
2. The Decoupling Limit of the Higgs sector

The Higgs boson serves as a window to physics beyond the Standard Model (BSM) only if one can experimentally establish deviations of Higgs couplings from their SM values, or discover new scalar degrees of freedom beyond the SM-like Higgs boson.

The prospects to achieve this are challenging in general due to the decoupling limit. In extended Higgs models, most of the parameter space typically yields a neutral CP Higgs boson with SM-like tree-level couplings and additional scalar states that are somewhat heavier in mass (of order $\Lambda_{\rm H}$), with small mass splittings of order $m_Z^2/\Lambda_{\rm H}$. Below the scale $\Lambda_{\rm H}$, the effective Higgs theory coincides with that of the SM.

In particular, the LHC search for MSSM Higgs bosons has produced interesting limits in the non-decoupling regime, where $m_A \lesssim 150$ GeV.





With more data, LHC data can be used to rule out more of the $\tan\beta$–m_A plane. However, in the region of large m_A and moderate $\tan\beta$, it will be difficult to detect H^0, A^0 and $H^\pm$ even with a significant increase of luminosity. This is the infamous *LHC wedge region*, where only the SM-like h^0 of the MSSM can be observed.

The general 2HDM

Consider the most general 2HDM potential,

$$\begin{aligned}\mathcal{V} = {} & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}] + \tfrac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 \\ & + \tfrac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ & + \left\{ \tfrac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \left[\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)\right] \Phi_1^\dagger \Phi_2 + \text{h.c.} \right\} .\end{aligned}$$

Define new linear combinations of the Higgs doublet fields (the so-called *Higgs basis*):

$$H_1 = (H_1^+ \,,\; H_1^0) \equiv \widehat{v}_a^{\,*} \Phi_a \,, \qquad\qquad H_2 = (H_2^+ \,,\; H_2^0) \equiv \epsilon_{ab} \widehat{v}_a \Phi_b \,,$$

where the vacuum expectation values of the two Higgs fields can be parametrized as

$$\langle \Phi_a \rangle = \frac{v}{\sqrt{2}} \begin{pmatrix} 0 \\ \widehat{v}_a \end{pmatrix} , \qquad \text{with} \qquad \widehat{v}_a \equiv e^{i\eta} \begin{pmatrix} \cos\beta \\ e^{i\xi} \sin\beta \end{pmatrix} ,$$

where $v = 246$ GeV, $0 \leq \beta \leq \frac{1}{2}\pi$ and η is arbitrary. It follows that

$$\langle H_1^0 \rangle = \frac{v}{\sqrt{2}} \,, \qquad\qquad \langle H_2^0 \rangle = 0 \,.$$

The Higgs basis is uniquely defined up to an overall rephasing, $H_2 \to e^{i\chi} H_2$. In the Higgs basis, the scalar potential is given by:

$$
\begin{aligned}
\mathcal{V} = {} & Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + [Y_3 H_1^\dagger H_2 + \text{h.c.}] + \tfrac{1}{2} Z_1 (H_1^\dagger H_1)^2 \\
& + \tfrac{1}{2} Z_2 (H_2^\dagger H_2)^2 + Z_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + Z_4 (H_1^\dagger H_2)(H_2^\dagger H_1) \\
& + \left\{ \tfrac{1}{2} Z_5 (H_1^\dagger H_2)^2 + \left[Z_6 (H_1^\dagger H_1) + Z_7 (H_2^\dagger H_2) \right] H_1^\dagger H_2 + \text{h.c.} \right\} ,
\end{aligned}
$$

where Y_1, Y_2 and $Z_1, \ldots, Z_4$ are real and uniquely defined, whereas Y_3, Z_5, Z_6 and Z_7 are complex and transform under the rephasing of H_2,

$$
[Y_3, Z_6, Z_7] \to e^{-i\chi} [Y_3, Z_6, Z_7] \quad \text{and} \quad Z_5 \to e^{-2i\chi} Z_5 \,.
$$

The three physical neutral Higgs boson mass-eigenstates are determined by diagonalizing a 3×3 real symmetric squared-mass matrix that is defined in the Higgs basis.* The diagonalizing matrix is a 3×3 real orthogonal matrix that depends on three angles: θ_{12}, θ_{13} and θ_{23}. Under the rephasing of H_2,

$$
\theta_{12}\,,\ \theta_{13} \text{ are invariant, and} \quad \theta_{23} \to \theta_{23} - \chi \,.
$$

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*For details, see H.E. Haber and D. O'Neil, "Basis-independent methods for the two-Higgs-doublet model. II: The significance of $\tan\beta$," *Phys. Rev.* **D74**, 015018 (2006) [hep-ph/0602242].

The decoupling limit in the general 2HDM

In the decoupling limit, one of the two Higgs doublets of the 2HDM receives a very large mass and is therefore decoupled from the theory. This is achieved when $Y_2 \gg v^2$ and $|Z_i| \lesssim \mathcal{O}(1)$ [for all i]. The effective low energy theory is then a one-Higgs-doublet model, i.e. the SM Higgs sector.

We order the neutral scalar masses according to $m_1 < m_{2,3}$ and define the Higgs mixing angles accordingly. The conditions for the decoupling limit are:

$$|\sin\theta_{12}| \lesssim \mathcal{O}\left(\frac{v^2}{m_2^2}\right) \ll 1\,, \qquad |\sin\theta_{13}| \lesssim \mathcal{O}\left(\frac{v^2}{m_3^2}\right) \ll 1\,,$$

$$\mathrm{Im}(Z_5\, e^{-2i\theta_{23}}) \lesssim \mathcal{O}\left(\frac{v^2}{m_3^2}\right) \ll 1\,.$$

In the decoupling limit, $m_1 \ll m_2, m_3, m_{H^\pm}$. In particular, the properties of h_1 coincide with the SM Higgs boson with $m_1^2 = Z_1 v^2$ up to corrections of $\mathcal{O}(v^4/m_{2,3}^2)$, and $m_2 \simeq m_3 \simeq m_{H^\pm}$ with squared mass splittings of $\mathcal{O}(v^2)$.

Far from the decoupling limit, one typically finds that all Higgs bosons have a similar mass of $\mathcal{O}(v)$ and $none$ are SM-like.

In the decoupling limit of a general 2HDM, the CP-violating and flavor-changing neutral Higgs couplings of the SM-like Higgs state h_1 are suppressed by factors of $\mathcal{O}(v^2/m^2_{2,3})$. In contrast, the corresponding interactions of the heavy neutral Higgs bosons (h_2 and h_3) and the charged Higgs bosons ($H^\pm$) can exhibit both CP-violating and flavor non-diagonal couplings.

The decoupling limit is a generic feature of extended Higgs sectors.[†]

- Thus, the observation of a SM-like Higgs boson does not rule out the possibility of an extended Higgs sector in the decoupling regime.

- A precision Higgs program can reveal small deviations from the decoupling limit, indicating the existence of a new heavy mass scale.

[†]However, if some terms of the Higgs potential are absent, it is possible that no decoupling limit may exist. In this case, the only way to have very large Higgs masses is to have large Higgs self-couplings.

The MSSM Higgs sector has a 2HDM structure and automatically conserves CP at tree level. The decoupling behavior of the MSSM Higgs sector is exhibited in the limit of $m_A \gg m_Z$, where the corresponding tree-level expressions are given by:

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta\,, \qquad\qquad m_H^2 \simeq m_A^2 + m_Z^2 \sin^2 2\beta\,,$$

$$m_{H^\pm}^2 = m_A^2 + m_W^2\,, \qquad\qquad \cos^2(\beta-\alpha) \simeq \frac{m_Z^4 \sin^2 4\beta}{4m_A^4}\,,$$

where $\beta-\alpha$ is the CP-even Higgs mixing angle in the Higgs basis. As expected, $m_A \simeq m_H \simeq m_{H^\pm}$, up to corrections of $\mathcal{O}(m_Z^2/m_A)$, and $\cos(\beta-\alpha)=0$ up to corrections of $\mathcal{O}(m_Z^2/m_A^2)$. In general, in the limit of $\cos(\beta-\alpha)\longrightarrow 0$, all the h^0 couplings to SM particles approach their SM limits. In particular, if λ_V is a Higgs coupling to vector bosons and λ_f is a Higgs couplings to fermions, then

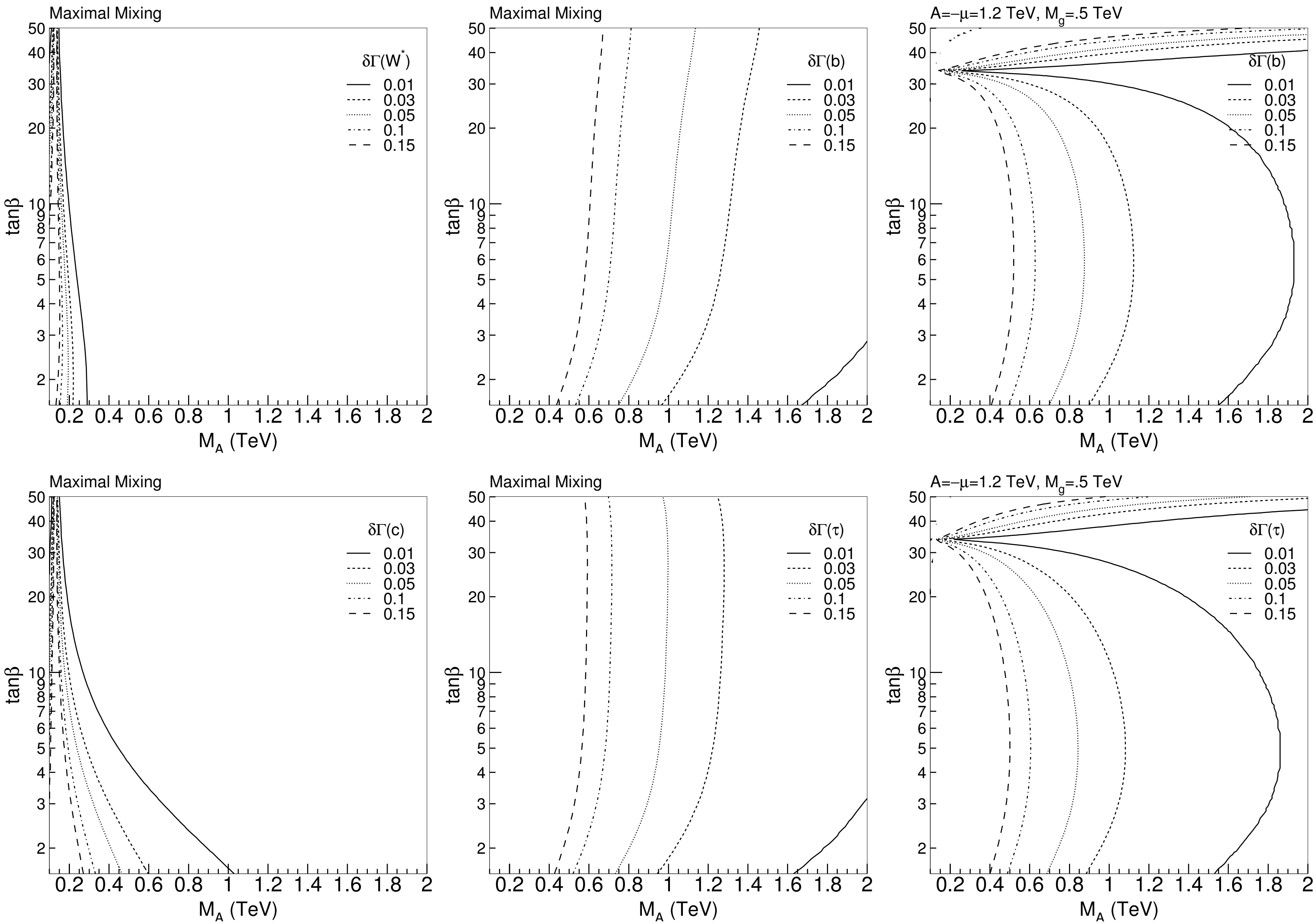
$$\frac{\lambda_V}{[\lambda_V]_{\rm SM}} = \sin(\beta-\alpha) = 1+\mathcal{O}\left(m_Z^4/m_A^4\right)\,, \qquad\qquad \frac{\lambda_f}{[\lambda_f]_{\rm SM}} = 1+\mathcal{O}\left(m_Z^2/m_A^2\right)\,.$$

The behavior of the $h^0 ff$ coupling is seen from:

$$h^0 b\bar{b} \quad (\text{or } h^0\tau^+\tau^-): \qquad -\frac{\sin\alpha}{\cos\beta} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)\,,$$

$$h^0 t\bar{t}: \qquad \frac{\cos\alpha}{\sin\beta} = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)\,,$$

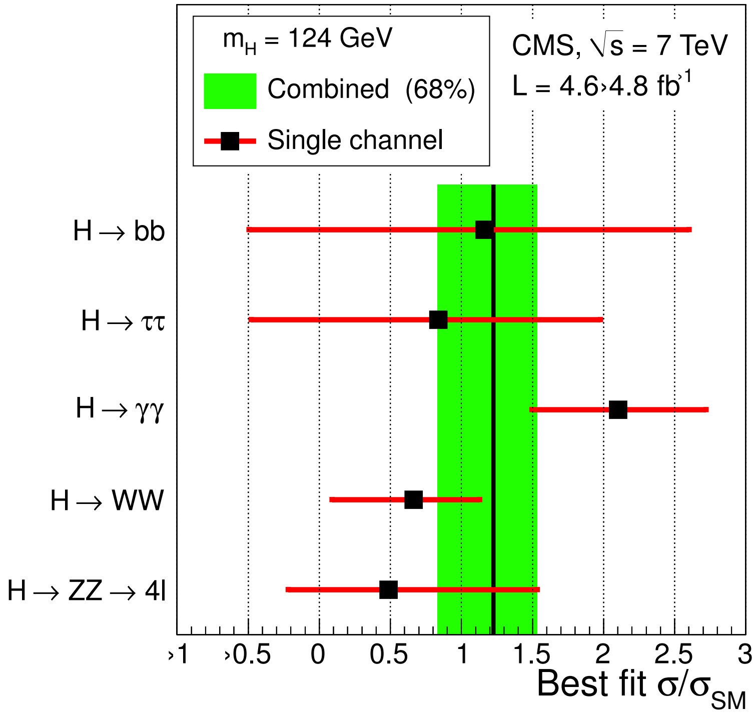
Note the extra $\tan\beta$ enhancement in the deviation of λ_{hbb} from $[\lambda_{hbb}]_{\rm SM}$.



Deviations of Higgs partial widths from their SM values in two different MSSM scenarios (Carena, Haber, Logan and Mrenna).

3. Interpreting deviations from SM Higgs behavior

If small deviations from SM Higgs properties are confirmed, they can be interpreted within the decoupling framework.



Values of $\mu \equiv \sigma/\sigma_{\rm SM}$ for the combination (solid vertical line) and for contributing channels (points), for a hypothesized Higgs boson mass of 124 GeV. The band corresponds to $\pm 1\sigma$ uncertainties on the overall μ value. The horizontal bars indicate $\pm 1\sigma$ uncertainties on the μ values for individual channels. (S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **710** (2012) 26).

Possible sources of deviations from SM Higgs behavior are:

- Non-decoupling in tree-level Higgs couplings associated with $\mathcal{O}(v^2/\Lambda_{\rm H}^2)$ arising from non-minimal Higgs physics
- Non-decoupling in loop-induced Higgs couplings due to BSM physics effects of order $\mathcal{O}(v^2/\Lambda_{\rm BSM}^2)$ appearing in the loops.

In principle, the scales $\Lambda_{\rm H}$ and $\Lambda_{\rm BSM}$ are unconnected. For example, in the MSSM, $\Lambda_{\rm H} \sim m_A$ and $\Lambda_{\rm BSM} \sim \Lambda_{\rm SUSY}$ (the supersymmetry-breaking scale).

In planning for a precision Higgs program at a future Higgs factory, one can consider two possible scenarios:

1. The Higgs boson is discovered at the LHC, with SM-like properties
2. The Higgs boson is discovered at the LHC, with properties that deviate from SM predictions.

The discovery or non-discovery of BSM physics at the LHC role will have a profound impact on the interpretation of the Higgs data.

Toward a precision Higgs program at a future Higgs factory

If a SM-like Higgs boson is discovered at the LHC with no evidence for BSM physics, then the Higgs factory will be critical for establishing whether the SM-like Higgs boson is *the* SM Higgs boson, and whether there is any evidence for small deviations from SM predictions (the first corrections to the decoupling limit), which could provide hints for the energy scale of BSM physics.

If the Higgs boson is discovered at the LHC, with small deviations from SM predictions, then a precision Higgs program can begin to unravel the non-decoupling corrections, with implications for the extended Higgs sector (if present) and the BSM physics that couples to the Higgs boson.

If the Higgs boson is discovered at the LHC, with large deviations from SM predictions, then it is likely that there are light degrees of freedom in the electroweak symmetry breaking sector (and the associated BSM physics) that can be probed directly at the Higgs factory.